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DUCTED PROPELLERS—A CRITICAL REVIEW

OF THE STATE OF THE ART

Contract No. Nonr 2677(00)

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DUCTED PROPELLERS - A CRITICAL REVIEW OF THE STATE OF THE ART

A Survey and Analysis for
the Office of Naval Research,
Department of the Navy

Office of Naval Research
Contract Nonr 2677(00)

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FOREWORD

This survey has been prepared for the Office of Naval Research in an effort to clarify the present state of knowledge regarding the aerodynamics of ducted propellers. It is hoped that this report will enable the reader to acquaint himself with the basic problems involved, the work that has been done up to the present time, its relative significance, and the areas in which further research appears to be needed.

A large number of individuals, companies, universities and government agencies (United States and foreign) have contributed to the survey. The authors wish to acknowledge the assistance and cooperation of those who were visited and of those who were helpful in providing reference material.

As many references as available, free from security and other restrictions, have been included in this report. In some cases references were provided the Contractor without the assurance that additional copies could be made available for further distribution. Information on the source of each document is given to the extent known. Most of the German publications can be obtained from Aerodynamische Versuchsanstalt Göttingen (AVA), if they are not available in the United States.

1. SUMMARY

A critical survey is made of the state of the art of ducted propellers. The survey is divided generally into theoretical and experimental research, and a comprehensive table of the latter is presented showing the type and extent of experimental investigations carried out. Specific reports are discussed where appropriate, and various aspects of the ducted propeller problem are considered in some detail. Finally, a summary of the state of the art is presented along with some recommendations for future research.

2. INTRODUCTION

The first serious experimental work on ducted propellers was evidently published in Italy in 1931 by Luigi Stipa (Ref. 97) who conducted systematic wind tunnel tests which clearly indicated the benefits to be gained by ducting or shrouding the propeller for static operation and low speed flight. Stipa's experiments, in which the propeller was placed essentially at the leading edge of a long hollow fuselage, were based on theoretical reasoning by Stipa, dating back to about 1927 (see Ref. 96), in which he likened the ducted propeller to an extended nozzle discharging from a plenum chamber. The results of Stipa's experiments were so promising that the Italian Government actually built an experimental airplane whose hollow fuselage comprised the ducted propeller. The control surfaces extended into the slipstream, and the airplane exhibited increased maneuverability and reduced landing speed (Ref. 99).

For some reason, however, in reports eminating from Europe, credit for the invention of the ducted propeller has generally been given to Kort (Ref. 39) whose paper was published in 1934 in Germany. In fact, the ducted propeller is frequently referred to as the "Kort nozzle". On the other hand, a Russian paper by Soloviev and Churmack (Ref. 94), published in 1948, contains a rather lengthy discussion which refers to a Russian paper by F. A. Bricks dated 1887 and therefore states:

> "These facts should prove that the Russian technological concept has priority over others and that the idea of adapting guide nozzles in hydraulic and aeronautical propellers should be credited to Russian scientists."

However, the classical experiments of Krüger (Ref. 41) were evidently carried out in Germany somewhat earlier than the comprehensive Russian experimental work referred to in Reference 94. The analytical work of Reference 94 also shows a strong similarity to the work of Küchemann and W[illegible] (Ref. 46), whose analysis was the basis for Krüger's experiments.

Since these early experiments in the '30's, interest in the ducted propeller has become more widespread, particularly now that hovering flight and vertical take-off have become entirely feasible. Consequently, research has since been carried out on this subject in a number of other countries including the Netherlands (Refs. 105, 106), France (Ref. 56), England (Refs. 5, 79), Australia (Refs. 75-78, 90, 108), and the Union of South Africa ([illegible], 107), as well as the United States. Very often, however, each investigation, particularly in the United States, represents an independent attempt to deal with some particular aspect of the problem, and a coordinated research program has evidently been lacking. As a result, it is difficult to find in the literature consistent and meaningful results which are directly applicable to the general ducted propeller problem. In order to alleviate this situation, the Office of Naval Research awarded a contract (Nonr 2677(00)) to the Advanced Research Division of Hiller Aircraft Corporation for the purpose of carrying out a critical survey of all available information on ducted propellers.

2.1 Approach to the Survey

The aim of this survey is to produce a clear picture of the state of the art and to indicate possible areas of future research. In order to do this, the following approach was taken:

1. All pertinent material for which our own library already had reference information was acquired, all reports listed as references therein were obtained, and so on. The services of ASTIA were also enlisted.

2. Letters of inquiry were sent out to all known authors and investigators in the field of ducted propellers both in this country and abroad. The companies, agencies and institutions which were contacted are listed in Appendix A.

3. All references in the material thus acquired were checked out.

4. All ducted propeller material was read and reviewed by at least one research aerodynamicist.

5. The results of this literature study were analyzed and personal visits were then made where appropriate. In some cases, telephone conversations and further correspondence were carried on. Visits were made to the following companies, agencies and institutions:

   David Taylor Model Basin, Washington, D. C.
   Doak Aircraft Company, Torrance, California
   Eastern Research Group, New York, New York
   Grumman Aircraft Engineering Corporation, Long Island, New York
   Massachusetts Institute of Technology, Cambridge, Massachusetts
   NASA Langley, Langley Field, Hampton, Virginia
   ONR, Air Branch, Washington, D. C.
   Princeton University, Princeton, New Jersey

United Aircraft Corporation, Hamilton Standard Division, Windsor Locks, Connecticut

United Aircraft Corporation, Research Department, East Hartford, Connecticut

Vertol Aircraft Corporation, Morton, Pennsylvania

6. On the basis of all of the information assimilated, the present report was prepared.

2.2 Ducted Fan Symposium

During the progress of the survey reported herein, a symposium was held at the Massachusetts Institute of Technology for the purpose of promoting an exchange of information among the various investigators in the field of ducted propellers. A list of the organizations in attendance and the papers made available through that symposium are presented in Appendix B.

3. GENERAL CONSIDERATIONS

3.1 Definition and Scope of Problem

In the present paper, the terms ducted fan and ducted (or shrouded) propeller are considered to be synonymous. In either case, we shall mean a propeller or fan which is circumscribed by a thin ring whose sole aerodynamic purpose is to increase the thrust produced by the entire unit. If the ring ceases to be thin in the axial direction, that is if the lateral extent of the ring approaches or exceeds its axial length, then the unit shall be considered as a fan-in-wing arrangement and will be treated separately. It seems clear that the fan-in-wing represents a different problem, since the circulation flow round the "duct" is restricted and modified by its lateral extent, particularly during static operation.

The ducted propeller is also distinguished from the compressor by virtue of its intended purpose; namely, that of producing thrust. The purpose of the compressor, on the other hand, is simply to produce an increase in pressure across the propeller disk. That these purposes are not necessarily compatible can perhaps best be demonstrated by considering the "efficiency" of a compressor and comparing it with that of a ducted propeller. This will be done in the following section.

3.2 Static Efficiency

The efficiency of a compressor in the static condition is defined in terms of the pressure rise Δp and the volumetric flow $A_p v$, where A_p is the fan disk area and v is the average velocity through the disk. Thus

$$\eta_s = \frac{\Delta p \cdot A_p v}{P} \tag{1}$$

where P is the power input. Since the numerator represents the energy added to the flow through the compressor, this expression can be written in the form

$$\eta_s = \frac{\text{slipstream kinetic energy}}{\text{power input}} \tag{2}$$

Now equation (2) can easily be applied to the open (unshrouded) propeller in the static condition, for which the slipstream velocity is just twice the velocity through the disk (Ref. 21). Thus, since the thrust T is equal to the rate of change of momentum,

$$T = \rho A_p v (2v) \tag{3}$$

where A_p is now propeller disk area. The static efficiency η_s would therefore be, from equations (2) and (3),

$$\eta_s = \frac{\frac{1}{2} \rho A_p v (2v)^2}{P} = \frac{T v}{P} = \frac{T}{P}\sqrt{\frac{T/A_p}{2\rho}} \tag{4}$$

Since this expression is identical with the usual "figure of merit" M used in helicopter performance, it is clear that, in the case of the open propeller, compressor efficiency is synonymous with hovering (thrust producing) efficiency.

Now let us consider the ducted propeller in the same manner. Here the final slipstream velocity v_f is no longer equal to twice the velocity through the disk, so we have, in terms of the final wake area, A_f,

$$T = \rho A_f v_f^2 \tag{5}$$

and

$$\eta_s = \frac{\frac{1}{2}\rho A_f v_f^3}{P} = \frac{T v_f}{2P} = \frac{T}{2P}\sqrt{\frac{T/A_f}{\rho}} \tag{6}$$

Since the area of the final wake of a ducted propeller is not known a priori, and is not easily measured, it is useful to express A_f in terms of the division of thrust T_p/T where T_p is the portion of thrust carried on the propeller. By application of Bernoulli's equation ahead of and behind the propeller disk, it can easily be shown that (if the duct losses are small compared with the disk loading) the pressure jump Δp across the propeller disk is equal to the dynamic pressure of the final wake. Thus, the propeller thrust is simply

$$T_p = \Delta p \cdot A_p = \frac{1}{2}\rho v_f^2 A_p \tag{7}$$

Therefore, from equations (5) and (7),

$$\frac{T_p}{T} = \frac{1}{2}\frac{A_p}{A_f} \tag{8}$$

so that equation (6) can finally be written as

$$\eta_s = \frac{T}{P}\sqrt{\frac{T/A_p}{2\rho}} \cdot \sqrt{\frac{T_p}{T}} \tag{9}$$

Thus, for a ducted propeller in the static condition, the compressor efficiency involves not only the figure of merit (ducted propeller efficiency) but also the division of thrust. From equation (9), it can be seen that, given an ideal compressor efficiency of 1.0, the attainment of a high static figure of merit (i.e., a high thrust per horsepower at a given disk loading) requires further that the shroud carry as high a fraction of the total thrust as possible. In other words, for the ideal case of 100% compressor efficiency ($\eta_s = 1.0$) we have

$$M_i = \frac{T}{P}\sqrt{\frac{T/A_p}{2\rho}} = \sqrt{\frac{T}{T_p}} \tag{10}$$

It must be pointed out that one could define the figure of merit in such a way as to make it identical with the compressor efficiency. This would simply amount to taking the expression of equation (6) as the definition of figure of merit. That is,

$$M' = \frac{T}{2P}\sqrt{\frac{T/A_f}{\rho}}$$

The difficulty with such a definition for the ducted propeller, however, stems from the fact that the final wake area A_f is not known. Therefore, in the present report, the figure of merit will be based on propeller disk area, so that from equation (9),

$$M = \eta_s \sqrt{\frac{T}{T_p}} \tag{11}$$

Since a rather wide range of T_p/T for ducted propellers has been observed exper[illegible] (see e.g. Ref. 41), it is therefore concluded that a good compressor design ($\eta_s \rightarrow 1.0$) does not necessarily produce a ducted propeller having a high figure of merit.

It might be noted here that, according to equation (10), the ideal figure of merit M_i is equal to unity only if $T = T_p$, which corresponds to the open propeller. As soon as the shroud carries any thrust at all, the ideal value of M exceeds unity and is limited only by the portion of thrust that can be carried on the shroud. The fact that M_i is greater than unity for the ducted propeller need not be a matter for concern, however, since it is not a true efficiency (as is η_s) but rather is simply a measure of the total thrust produced per horsepower at a given disk loading.

For the reasons discussed above, the present survey report will be concerned primarily with the ducted propeller (or ducted fan) itself as an entity and will not attempt to deal with the mass of theoretical and experimental data pertaining to open propellers, ring wings, and compressors, all of which are considered to be outside the scope of this report.

3.3 Presentation of Results

The papers analyzed for this report can be divided essentially into experimental and theoretical investigations. Since the experimental work lends itself to a tabulation of variables investigated and measurements taken, such tables have been prepared (see Tables I, II and III) with appropriate remarks. The tables and the papers appearing in the tables will be discussed at some length in section 4.2, page 26. On the other hand, the details of the theoretical work have differed so much from one paper to the next that similar tables were not feasible. Instead, in section 4.1, page 13, the main theoretical methods are outlined and discussed, and the approaches taken by the various authors are considered.

Finally, the list of references contains the material reviewed which was considered to lie within the scope of the present study, as described previously.

4. SURVEY OF PUBLISHED DUCTED PROPELLER WORK

The addition of the ring or shroud to the propeller has produced not only a new problem, but a vastly more difficult one than the open propeller. The primary reason for this is that the mutual influence between propeller and shroud is such that the aerodynamic behavior of the ducted propeller is quite different from that of either the open propeller or the ring wing. In addition, the number of variables is actually so large as to make a comprehensive study (either experimental or theoretical) extremely difficult. The geometric variables of the problem can conveniently be divided into duct variables, propeller variables, and overall or combined variables. Thus, a preliminary list might be

A. Duct variables

1. chord/diameter ratio
2. profile thickness/chord ratio
3. profile camber
4. leading edge radius
5. chord line orientation relative to axis
6. profile trailing edge angle
7. position of maximum thickness

B. Propeller variables

1. solidity
2. overall pitch setting
3. pitch distribution (twist)
4. blade profile (thickness, camber, etc.)
5. chord distribution (taper)

C. Overall variables

1. propeller location within shroud
2. ratio of hub diameter to propeller diameter
3. clearance between blade tips and duct surface
4. centerbody shape (nose shape, tail shape, location of maximum thickness, etc.)
5. centerbody location relative to shroud

In addition to these purely geometric variables, there are of course the aerodynamic variables of angle of attack, advance ratio, Reynolds number, and Mach number. Thus, the enormity of the problem becomes apparent and would seem to indicate that the probability of arriving at an optimum ducted propeller design by experiment is essentially nil. The development of a highly efficient ducted propeller will therefore evidently require a sound theoretical development supported by carefully selected systematic experiments. The pitfalls of investigating the effect of a single variable with the other variables arbitrarily fixed should be apparent from the above discussion. This point will be discussed further in the section on experimental programs.

The survey of the published ducted propeller work is divided into five main categories in this report. The first two deal respectively with theoretical and experimental research pertaining to the ducted propeller problem itself. Thus, mostly single ducted propeller arrangements are considered in these sections, with emphasis on systematic approaches aimed at evaluating the aerodynamic effects of the variables listed above. The third section is concerned with comparisons of theory with experiment, and the fourth deals with auxiliary devices, such as extensible slats, retractable flaps, vanes, and boundary layer control devices, which are aimed at improving ducted propeller performance and control. The final section is concerned with other problems relating to the ducted propeller, such as stability characteristics and the effects of interfering bodies, such as additional ducts (as in aerial jeep configurations), wing surfaces (fan-in-wing arrangments), ground effects, and the like.

4.1 Theory

The general theoretical problem of the ducted propeller can be stated as follows: Given a ring airfoil of specified camber line and thickness distribution, inside of which exists a pressure discontinuity (normal to the axis of symmetry) representing the propeller disk, determine the flow field produced in the presence of a uniform free stream of arbitrary direction and magnitude.[1] From the details of the flow field, one could of course, by integrating pressures over the various surfaces, determine the aerodynamic forces and moments as well as overall efficiency. The Kutta condition of finite fluid velocity is to be satisfied at the duct trailing edge, and the static pressure in the slipstream must finally return to the free-stream value at infinity.

The problem stated above can be conveniently divided into three flight conditions, each more or less representing a range of flight speeds for VTOL

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[1] Because of the inherent high drag of the shroud at high speeds, practical interest in the ducted propeller has been generally restricted to the low or middle subsonic speed range (e.g., Refs. 72, 73).

aircraft. These are: static operation (hovering flight), axial flow (high-speed forward flight or vertical climb), and non-axial flow (transitional flight). There are certain features which distinguish these regimes insofar as the mathematical treatment is concerned. In the static condition, for example, all the fluid from infinity in all directions must pass through the propeller disk, so there is no dividing streamline which separates the "internal" and "external" flow. The non-axial flow regime, on the other hand, is distinguished by the fact that the shape of the wake centerline is unknown, as well as the shape of the wake itself. The axial flow regime presents perhaps the most straightforward mathematical problem, and has received the largest share of attention from theoretical workers.

Since most of the theoretical work which has been done on ducted propellers and is available in the literature is concerned with axial flow, it is perhaps best to divide this work according to method of analysis. The three general categories of analyses chosen are: (1) those employing the classical method of singularities, (2) those employing strictly momentum considerations, and (3) those employing combinations of these or other techniques.

4.1.1 Method of Singularities

The mathematical expressions for the velocities induced throughout an infinite, ideal, incompressible fluid due to a potential vortex ring have been known for many years (see e.g., Ref. 47). Furthermore, the superposition of any number of such singularities to produce an arbitrary distribution of circulation strength (as along the chord of a duct) is a classical technique employed in the solution of problems in hydrodynamics (see e.g., Ref. 45). With these implements at hand, the mathematical problem of the ducted propeller (of zero shroud thickness) can be stated in one of two ways, as follows: calculate the shroud camber line associated with a given chordwise vorticity distribution (or vice versa). For axial flow, or for the static condition, the procedure is briefly as follows:

1) Place the specified distribution of vortex rings along a semi-infinite circular cylinder representing the ducted propeller and its wake, with the axis of symmetry in the free-stream direction. The vortex strength per unit length is constant behind the shroud trailing edge and the Kutta condition is to be satisfied at the trailing edge. Calculate the axial and radial components of induced velocities caused by this distribution of vortex rings, using the integral expressions given in Reference 45. These expressions involve elliptic integrals of both the first and second kinds and are rather cumbersome.

2) Impose the boundary condition that the normal velocity at the shroud surface must vanish everywhere, so that the resultant velocity is parallel to the surface. Thus,

$$\frac{dR}{dx} = \frac{v_r}{V_o + v_x}$$

where v_r and v_x are the radial and axial components of the induced velocity associated with the given vortex distribution. They are obtained from the integrals written in (1) above. The resulting function R(x) defines the duct camber line to a first approximation.

3) An iteration can be performed by displacing the distribution of vortex rings from the original assumed circular cylinder onto the calculated camber line and its wake and repeating steps (1) and (2). This process is extremely cumbersome and is ordinarily omitted.

It should be pointed out that the problem outlined above is the determination of the flow field, and consequently the performance, of a ducted propeller of specified chordwise vorticity distribution. In a similar fashion, one could determine the vorticity distribution associated with a specified shroud shape. The effects of duct profile thickness and of centerbodies could also be included by the use of additional distributed singularities. However, perhaps the problem of greatest practical interest is the determination of an optimum design for best performance. The assumption of either the shroud vorticity distribution or the shroud shape, which is required for the procedure outlined above, precludes the determination of a truly optimum design. It appears, therefore, that some further mathematical condition or relationship is required before an optimum vorticity distribution and the associated shroud shape can be determined. If this could be done, however, the velocity distribution at the propeller disk could then be calculated for any location of the propeller. The appropriate propeller blades could then be designed by existing methods.

If the chord/diameter ratio of the shroud is sufficiently small, then the asymptotic expansion of the elliptic integrals in the velocity components v_r and v_x simplifies the equation of step (2) immensely. Then if each section of the shroud is treated as a two-dimensional thin airfoil, fairly simple analytical solutions can be obtained by means of conformal mapping. This mathematical device was employed by Burggraf (Ref. 2) and enabled him to predict mathematically the entire pressure distribution and consequently the forces and moments acting on the shroud in various flight conditions. The case of non-axial flow was included, under the assumption that the wake forms a cylindrical extension of the shroud in the direction of the duct axis. This assumption, of course, limits the analysis to forward speeds which are small compared with wake velocity, but the analysis of Reference 2 represents the only attempt at an application of the method of singularities to a ducted propeller in non-axial flow.

More approximate solutions can be obtained, without the assumption of a small chord/diameter ratio, by assuming the mathematical form of the shroud vorticity distribution (with unspecified coefficients for each term) and satisfying the boundary condition at a number of points on the shroud equal to the number of unknown coefficients. This approach was taken by Helmbold (Ref. 29), who employed a vorticity distribution with a leading-edge singularity and calculated the performance of a family of shrouds having assumed parabolic camber lines. (In a later paper, Helmbold considered the effect of compressibility on these calculations by applying the Prandtl-Glauert correction to the wake (see Ref. 30).) On the other hand, Dickmann and Weissinger (Ref. 15), who employed an elliptic vorticity distribution, assumed the entire vorticity distribution (except for one parameter corresponding to the pressure jump across the propeller disk) and calculated the required shroud camber lines for various loadings by integrating the slopes given by the boundary condition on the shroud surface. An elliptic vorticity distribution was also assumed by Lerbs (Ref. 48), who carried out a similar comprehensive analysis but did not present explicit results in the form of shroud shapes. Both of these reports (Refs. 15 and 48) represent comprehensive treatises of the shrouded propeller problem but suffer from the limitation of an assumed elliptic vorticity distribution. Consequently, the explicit shroud shapes calculated represent a rather special class of shapes. In the same sense, the shapes treated by Burggraf and Helmbold represent other special classes (flat and parabolic, respectively) of shroud profiles. Burggraf's analysis, however, is the only one in which the mathematical form of the vorticity distribution was not assumed. On the other hand, Pivko (Ref. 81) who assumed a small chord/diameter ratio, makes the addtional assumption that the pertubation velocities are small compared to the flight velocity. Such calculations are, of course, invalid for low flight speeds and particularly for the static condition. The theoretical basis upon which all of the above works rest is developed and discussed in Reference 45, which also considers the increase in mass flow through the propeller caused by the duct and points out t reasons that ducted propellers show considerably more promise for static and low-speed operation than for high speeds. The mathematics of the general ducted propeller problem were also set out and further developed by Dickmann in Reference 16.

4.1.2 Momentum Methods

The application of Newton's second law to the ducted propeller problem quickly yields relationships between thrust and power which are of considerable interest and value. Thus, the total thrust of a ducted propeller in axial flow can be expressed as the product of the mass flow per unit time through the duct and the change in velocity from infinity ahead to infinity behind the duct. That is,

$$T = \rho A_f v_f (v_f - V_o) \tag{12}$$

where the subscript o refers to infinity upstream and f to infinity downstream (inside the slipstream). A_f is thus the area of the final wake. (A list of symbols can be found in Appendix C.)

It can easily be shown (Ref. 21) that, for minimum power expended, the final wake velocity v_f, must be constant. This does not, however, imply anything about the velocity distribution within the shroud (or at the shroud trailing edge), which must depend on the details of the configuration. In a similar manner, the power required in axial flow (in the absence of duct losses, blade profile drag, etc.) can be expressed as the change of kinetic energy per unit time. Thus,

$$P_i = \frac{1}{2} \rho A_f v_f (v_f^2 - V_o^2) \tag{13}$$

From equations (12) and (13), then, one can express the ideal value of either propulsive efficiency $\frac{T V_o}{P}$ or static efficiency (figure of merit) $\frac{T}{P}\sqrt{\frac{T/A_p}{2\rho}}$ in terms of the area and velocity of the final wake. Thus, the ideal propulsive efficiency is simply

$$\eta_i = \frac{T V_o}{P_i} = \frac{2}{1 + v_f/V_o} \tag{14}$$

Furthermore, the propeller thrust T_p can be expressed simply as the product of propeller disk area A_p by the pressure jump Δp across it. Application of

Bernoulli's equation ahead of and behind the disk shows this pressure jump to be equal to the difference between the initial and final dynamic pressure, so that

$$T_p = A_p \cdot \frac{1}{2} \rho \left(v_f^2 - V_o^2\right) \tag{15}$$

and the above efficiencies can then be expressed in terms of the division of thrust between propeller and shroud. Thus, in the static condition ($V_o = 0$) the ideal figure of merit M_i can be written as

$$M_i = \frac{T}{P_i} \sqrt{\frac{T/A_p}{2\rho}} = \sqrt{\frac{T}{T_p}} \tag{16}$$

which states that the ideal figure of merit increases as more of the thrust load is shifted onto the shroud. Similarly, the propulsive efficiency η_i can be conveniently expressed in terms of the propeller thrust coefficient defined as

$$C_{T_p} = \frac{T_p}{\frac{1}{2} \rho V_o^2 A_p} \tag{17}$$

Thus, introducing equation (15), equation (14) becomes

$$\eta_i = \frac{2}{1 + \sqrt{1 + C_{T_p}}} \tag{18}$$

which indicates that the ideal propulsive efficiency depends only on the propeller loading coefficient. This development was demonstrated by Küchemann and Weber (Refs. 44 and 45) who introduced an incremental velocity δ through the propeller disk as produced by the shroud. Küchemann and Weber showed further that if the drag of the shroud is considered, then the propulsive efficiency depends on the overall loading as well as on the propeller loading,

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so that the propulsive efficiency becomes a function of δ. This fact was used in Reference 46 in which the incremental velocity δ due to the shroud was actually determined by measuring the advance ratio for zero thrust both with and without the shroud.

It is worth noting that none of the above equations offers either a value for the ideal efficiency or an explicit relationship between the geometry of the configuration and its efficiency. In other words, these momentum relationships do not suffice to predict the performance of a ducted propeller. At the present time, there appears to be no known method of linking the unknown wake characteristics (A_f and v_f) with the duct design without resorting to the method of singularities (including iteration) as discussed in the previous section. In order to avoid this difficulty, an assumption is ordinarily introduced into the analysis relating the duct exit characteristics with the final wake.

The most common assumption, forming what we shall call here "simple momentum theory" is that the duct exit area is equal to the final wake area (i.e., $A_e = A_f$). It can be shown, by applying the equations of continuity and momentum to the wake itself, that this assumption also implies that (1) the velocity distribution at the shroud exit is uniform, and (2) the static pressure at the shroud exit is equal to that at infinity (referred to as ambient pressure). In other words, in simple momentum theory, the entire character of the wake is assumed. It is taken to be a cylindrical wake of constant diameter, constant pressure, and constant velocity from the duct trailing edge to infinity downstream. With this assumption, since $A_f = A_e$, equations (12) and (15) yield, for the static case ($V_o = 0$), a division of thrust of $T_p/T = 1/2\ A_p/A_e$. Furthermore, if there is no diffuser, $A_e = A_p$ and the division of thrust T_p/T becomes 1/2. Substitution of this value into equation (16) then results in a value of $\sqrt{2}$ for the ideal figure of merit.

Examples of the simple momentum theory discussed above are found throughout the literature as applied to both axial flow (Refs. 51, 65, 82, 85, 91, 100, 102, 107 and 113) and non-axial flow (Refs. 49 and 89). The non-axial flow case is generally based on the assumption of an axial slipstream at the duct exit, an assumption which is valid provided that the duct chord/diameter ratio is sufficiently large and that the forward speed is small compared with the wake velocity.

A second, less common and somewhat less restrictive assumption in regard to the final wake area relates the wake area to the cross-sectional area and diffuser angle at the trailing edge of the duct. This assumption has been discussed by Weinig in Reference 111 which brings out clearly the importance of the characteristics of the final wake. The mathematical statement, which admits of some expansion of the wake behind the duct trailing edge and is based on the work of Trefftz (Ref. 103), reads as follows:

$$\frac{A_f}{A_e} = \frac{1}{1 - 0.45\,\theta} \qquad (19)$$

where θ is the angle of inclination of the inside surface of the duct trailing edge with respect to the duct axis. This relationship and others pertinent to the wake have also been considered at some length by Krüger (Ref. 41). Equation (19) above is, of course, in practice restricted to small values of θ unless some means of boundary layer control is applied.

In some of the literature (e.g., Refs. 60, 61 and 64), neither of the above assumptions is introduced, but instead all quantities are expressed in terms of the duct exit static pressure, which is also unknown. At this point, either the exit static pressure is assumed to be uniform and equal to ambient pressure, which results in the simple momentum theory discussed above, or else the problem is divided into various regimes with only limiting cases treated (e.g., Ref. 60). In any case, the fact remains that the conditions across the duct exit and their relationship to overall ducted propeller efficiency are as yet uncertain.

In an effort to achieve more realistic predictions of performance than are sometimes afforded by simple momentum theory, various authors have introduced refinements in the form of losses due to duct skin friction, blade profile drag, compressibility, slipstream rotation, etc. (see Refs. 5, 10, 59, 64 and 95). However, the basic assumption of uniform velocity in the duct is retained, and additional assumptions are ordinarily introduced for the estimation of such items as the shroud friction drag.

4.1.3 Other Methods

The mathematical difficulties encountered in the method of singularities have led many investigators to seek approximate methods which would render the mathematics more tractable and yet would yield more detailed results than the simple momentum theory is capable of supplying. Efforts in this direction can be generally divided into two major categories: (1) those placing emphasis on the propeller, and (2) those placing emphasis on the shroud.

The former group tends to start with blade-element theory, as developed for open rotors (e.g., Refs. 31, 66 and 67) and modifies the blade-element theory to take some account of the influence of the shroud.

A number of papers have been written in which hovering or axial flow is considered and the blades are designed as in a compressor. (See e.g., Refs. 6, 7, 8, 75-78, 107 and 108.) In many instances, the flow through the propeller disk is assumed to be uniform (e.g., Refs. 6, 7, 8 and 107), and in this case the ideal performance (i.e., with no losses) agrees with that predicted by simple momentum theory.

In tilted forward flight (non-axial flow) the above approach can be expected to yield reasonable results for cases in which the deflection of the airstream caused by the shroud is relatively small, so that the ducted propeller behaves similarly to a helicopter rotor. This approach has been taken, for example, by Moser and Livingston (Refs. 66 and 67) who developed semi-empirical expressions for the aerodynamic characteristics of ducted fans in tilted forward flight.

The second approach, in which the emphasis is on the shroud, usually consists of an approximation to the method of singularities. For example, the shroud may be represented approximately by a single vortex ring. This approach was taken for the case of axial flow by Allen and Rogallo (Ref. 4) who assumed that the core of the single vortex had the same perimeter as the airfoil section of the duct profile. The single vortex ring was also used in Reference 89 to calculate the equilibrium pitching moments on an isolated ducted fan in forward flight. It should be pointed out here that the use of a single ring vortex and the assumption of a uniform velocity distribution through the propeller are not compatible, owing to the nature of the velocity field induced by the ring. The single ring vortex has also been used in combination with a single source (or sink) and with a distribution of sources by Horn (Ref. 34) to represent the ducted propeller in axial flow.

The case of the ducted propeller in non-axial flow has been treated as a ring wing by Minassian (Ref. 63), who assumed that the propeller caused the internal pressures on the shroud to cancel. He then applied two-dimensional airfoil characteristics to predict the variation of total normal force with angle of attack. These assumptions are evidently approximately valid for small angles of attack and high advance ratios.

An electrical analogue to the method of singularities has been developed for three-dimensional potential flow problems by Malavard (Ref. 56), who has applied this technique to the ducted propeller problem. The boundary conditions are satisfied by the application of appropriate electrical potentials at the shroud and at the wake boundary which is assumed to be of constant diameter.

In summary, it can be stated that the theoretical approach to the ducted propeller problem has been established along classical lines, and that the mathematical means are at our disposal for solving this problem, provided that either the shroud camber line or the shroud vorticity distribution is specified. However, there is as yet no known method of calculating either the optimum shroud shape or the optimum vorticity distribution for best overall performance. Once the shroud shape is determined and the propeller position is specified, the velocity distribution through the disk and the required propeller twist can be calculated by existing or modified propeller design techniques (e.g., Refs. 75-78 and 108).

4.2 Experiment

The experimental work on ducted propellers which has been carried out and published can conveniently be divided into three categories which correspond to the three flight regimes of VTOL aircraft:

1) Static operation (hovering flight)
2) Axial flow (high-speed flight)
3) Non-axial flow (transitional flight)

Here again, as in section 4.1, we shall be concerned chiefly with investigations of the fundamental aerodynamics of the ducted propeller. Consequently, experimental investigations whose only or main purpose is to develop an auxiliary control device or to investigate the characteristics of a particular ducted propeller vehicle may be relegated to one of the next two sections titled respectively, Auxiliary Devices and Related Problems.

The investigation of static performance lends itself nicely to outdoor full-scale testing, and in some cases this technique has been employed, although extraneous air currents can cause some difficulty (e.g., Ref. 82). Another technique is the use of a scale model in a large room, but the question of how large the room must be is not a simple one, and the answer depends upon the disk loading of the model. This question becomes especially pertinent when "static" data are obtained in a wind tunnel, as in the case of Krüger (Ref. 41) who points out that his static data actually corresponds to an advance ratio (tunnel speed/tip speed) of about 0.03, causing noticeable effects on the calculated figure of merit. The very fact that a wind tunnel is not required for performing static tests, however, has generally produced a larger quantity of data in the static regime than in the other two.

The axial flow regime is the one most familiar to propeller specialists and is treated in many text books (e.g., Ref. 21), in which the appropriate tunnel wall corrections are derived for application to wind tunnel measurements. Consequently, wind tunnel investigations of the axial flow regime present no serious obstacles regarding the reduction of the data.

The non-axial flow regime, on the other hand, presents a rather serious problem in regard to wind tunnel testing. At low tunnel speeds, with the duct axis inclined at large angles to the tunnel axis, the slipstream deflection caused by the tunnel walls affects the entire flow field surrounding the model to such an extent that the tunnel wall corrections may become quite large, particularly at high disk loadings. The usual downwash corrections for wings are not applicable because of the large downwash angles involved and because of the completely different nature of the vortex wake. At the present time, there exists no theory of wind tunnel wall corrections for ducted propellers in non-axial or low-speed flow. Estimates are sometimes made of the tunnel wall effects in the static or hovering condition by testing both inside and outside the tunnel, but the wall effects at low tunnel speeds and high angles of attack remain unknown.

Specific information regarding the experimental research to dis- cussed here has been arranged in tabular form for each of the three regimes discussed above. Thus, Tables I, II and III summarize, respectively, the pertinent static, axial flow and non-axial flow tests performed on ducted propellers up to the present time.[2] The items listed in the tables fall either into the category of parameters which were varied or of measurements which were taken during the test. The significance of these particular variables and measurements will be discussed in the following paragraphs.

4.2.1 Parameters Varied

The large number of geometric variables listed in section 4 has been condensed into a few more inclusive categories in the preparation of Tables I, II and III. Thus, "duct shape" includes all such variables as chord/diameter ratio, duct profile, leading edge radius, diffuser angle, etc. Such a condensation seems useful in the light of the large number of tests conducted with an arbitrarily chosen duct design, usually to investigate the effect of some other variable. It must be recognized, of course, that the effect of (say) propeller location might be quite different in two ducts of different design. Similarly, one could arrive at misleading conclusions by attempting to predict the effects of changing the propeller blade twist by using data from another ducted propeller whose propeller is in a different axial location within the duct and hence in a region having a different velocity distribution (Ref. 45).

[2] Because of the lack of knowledge regarding scale effects and wind tunnel wall corrections, tests which were made outdoors or with full-scale models are noted in the remarks column.

a. Duct shape

The tests in which the most systematic variations of duct shape over a rather wide range were achieved appear to be those of Stipa (Ref. 97), Krüger (Ref. 41), Soloviev and Churmack (Ref. 94), van Manen (Refs. 105, 106), Küchemann and Weber (Ref. 46), Regenscheit (Ref. 86), and Evans (Ref. 1).[3] It is interesting to note that all of these tests except the last (Ref. 1) were restricted to axial flow, and Reference 86 was further restricted to the static case. On the other hand, Reference 1, which included non-axial flow, was restricted to small values of chord/diameter ratio, as were the experiments of Reference 86. At the other end of the spectrum are the experiments of Stipa, which were restricted to very large values of chord/diameter ratio. Both the Russian (Ref. 94) and Dutch (Refs. 105, 106) experiments were performed in water, and the propellers of the former were of essentially nautical design. The position of the propeller varied widely among the various tests, with no apparent attempt at a systematic investigation of that parameter except in Reference 1. Stipa's model had the propeller slightly ahead of the duct leading edge, Krüger's propeller position varied, and Regenscheit's was near the duct trailing edge. The remaining tests for which a check mark appears in the duct shape column were generally limited to tests of only two or three different ducts (e.g., Refs. 16, 26, 82 and 113) or to systematic variations in one or two very specific details of the duct shape; for example, leading edge radius, etc. (Refs. 46 and 74) or a given duct with auxiliary

[3] Rather detailed studies of the effects of lip shape on cowlings (no propeller inside the duct) are contained in Reference 71.

slats added (e.g., Ref. 37).

b. Blade pitch

The importance of varying the propeller blade pitch setting in ducted propeller tests can hardly be overemphasized. Since the theory cannot reliably predict the optimum blade pitch, and since the optimum pitch must depend upon the ducted propeller configuration, the significance of the test results may be severly impaired if the blade pitch is not varied over a sufficiently wide range of angles to insure that an optimum pitch setting is attained for each condition tested. In particular, results from which improvements in performance are attributed to a change of another parameter may be quite misleading if this requirement is not satisfied. For this reason, two columns are devoted to this item for the static and axial flow regimes (Tables I and II), in which the criterion for an optimum pitch setting has been clearly established. That is, in the static condition the attainment of a maximum figure of merit M is synonymous with optimum pitch setting;[4] in axial flow, the attainment of a maximum propulsive efficiency η is the proper criterion. (See section 4.1.2.) In non-axial flow, with the ducted propeller supplying lift as well as propulsion, the proper criterion is not so apparent, but it would seem that an equivalent lift/drag ratio defined as

$$\varepsilon = \frac{LV_o}{P - FV_o}$$

[4]It should be noted that the achievement of a uniform velocity distribution at the duct exit does not necessarily imply the attainment of a maximum figure of merit. The theory states only that the distribution of the final wake must be uniform for minimum power expended.

might be a reasonable measure of efficiency, where F is the net propulsive force of the device. (This criterion was used in Ref. 18.) It will be noted from Tables I and II that the optimum pitch setting was not attained in all tests in which the pitch was varied.

c. Propellers

Two columns of the experimental tables are devoted to the variation of propeller blade design and the number of propeller blades. In relatively few cases were both the blade design (planform, twist, etc.) and the number of blades varied. In fact, for non-axial flow, only in Reference 13 were these parameters varied. For static and axial flow, in some cases (e.g., Refs. 13, 46, 58 and 87), one or both of these were varied, but the pitch setting was fixed; in other cases (e.g., Refs. 24 and 58), both of these propeller parameters were varied, but the duct shape was fixed in advance.

By far the most common variations of blade design tested have been solidity (either blade width or number of blades) and blade twist. The latter variable has evidently been the source of controversy regarding the question of its importance in attaining high static performance. On the one hand, the experiments of several investigators (e.g., Refs. 13 and 58) indicate that, because of the nonuniform flow at the propeller plane (higher velocity toward the blade tips) which is induced by the shroud, the twist of the propeller must be such as to match that velocity distribution rather than the often assumed uniform flow. References 13 and 58 show gains in static efficiency achieved by such a redesign of a given propeller. On the other hand, References 18 and 41 show no such corresponding improvements in static efficiency and indicate that blade twist is relatively unimportant. Reference 67 also indicates a rather small effect of twist, except at the highest collective pitch tested.

There are several points worth discussing in regard to this apparent disagreement. First of all, in both References 18 and 41, the variation of figure of merit with pitch setting was determined for each blade twist by making direct measurements of thrust and power. Thus, the maximum efficiency of each propeller was directly compared. (These maxima may occur at a different blade pitch setting for each propeller.) Neither Reference 13 or Reference 58 shows the variation of figure of merit with pitch setting for each blade twist nor is any statement made regarding the optimum pitch setting for each twist. It is therefore difficult to distinguish between the effects of twist and those of blade pitch.

4.2.2 Quantities Measured

a. Total forces

In almost all the experimental work of Tables I, II and III, the total thrust or total forces acting on the model were measured directly. A notable exception is the work of Grose (Ref. 26) in which both the propeller and duct forces were measured individually and the sum was taken as the total force.[5] Another exception is the experimental work of Hubbard (Ref. 35) in which only the shroud thrust was measured, since the main interest there was in the sound generation of ducted propellers. However,

[5] Reference 26 represents the only available high-speed data on ducted propellers.

Hubbard's work contains practically the only data available on propeller-shroud tip clearance effects.[6]

b. Power

If the efficiency of a ducted propeller unit is to be determined experimentally, a direct measurement of the power supplied to the propeller is essential. Such a measurement is difficult, however, because of transmission losses, motor friction, etc. Almost all of the references tabulated contain some sort of power measurements, although some of these are considered to be approximate. The free-flight tests of McKinney (Ref. 57) contain no power measurements at all since the interest was clearly focused on flight characteristics. In some cases (e.g., Ref. 11), the power was estimated from the propeller RPM and is not considered to be accurate. It should be mentioned here that direct power measurements cannot ordinarily be satisfactorily replaced by slipstream velocity surveys[7] or by estimates based on manufacturer's charts. It is worth noting that the non-axial flow experiments of Parlett (Ref. 74) contain rather extensive data on the forces and moments but no power measurements.

c. Total moments

In the non-axial flow regime, the pitching moments may be of major importance, depending on the application intended for the ducted propeller.

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[6]The effects of tip clearance as applied to a compressor were studied in References 17 and 36.

[7]In the static case, the assumption that the slipstream kinetic energy is equal to the power input implies a compressor efficiency η_s of 100% (see page 7).

These moments were measured in all the references in Table III except in the flight tests of Reference 57 and in the wind tunnel tests of Reference 26 which were restricted to small angles of attack.

d. Division of forces and moments

The division of forces and moments between the propeller and shroud has been less frequently determined, except in the static case (Table I), although this division is related to the overall efficiency (see section 3.2) and is certainly of importance in developing an understanding of the flow fields associated with ducted propellers in general. The determination of the forces on the duct is naturally simpler and hence more common than the determination of propeller forces. In fact, in the non-axial case (Table III), References 67 and 26 appear to be the only ones in which direct measurements of the forces acting on the propeller were made, and Reference 26 did not measure the propeller normal force. In no case was the moment acting on the propeller measured.

Since the forces acting on the duct can be determined either from pressure distributions or from direct force measurements, and since the results of these measurements must differ, owing to friction losses at the duct surface, the two methods have been distinguished in the tables. In some cases (e.g., Refs. 4, 34, 41, 82 and 94), both methods were employed as a check, which is, of course, highly desirable. Although pressure distributions are extremely useful in learning the details of the surface flow, it must be recognized that direct force measurements are generally more reliable in determining the total forces acting on the duct. In contrast to the number of duct force measurements, the moment acting on the duct was measured in only one case (Ref. 18). However, the measurements of Reference 18 were no doubt influenced by flow separation which was observed on three of the four ducts tested.

e. Pressure distribution and velocity survey

The details of the flow field are perhaps best exhibited when both duct pressure distributions and velocity surveys inside or outside the duct are made. It can be seen from the tables that relatively few investigators observed both of these items. In fact, in the non-axial flow regime (Table III), Reference 67 is evidently the only one. Even in the axial flow regime (Table II), there are only three cases (Refs. 4, 41 and 58) in which such measurements were made. In the static case (Table I), a number of investigators took pressure distribution measurements and made velocity surveys.[8]

One of the most detailed studies for the static case is the early work of Platt (Ref. 82) who observed flow separation from the duct leading edge at low propeller RPM. But in axial flow, Krüger (Ref. 41) obtained pressure distributions on a number of different ducts both with and without propellers. Krüger's report also contains limited smoke studies of the wake behind ducted propellers. For the static case, perhaps the most extensive collection of velocity surveys within the duct (for a given duct with various propellers) appears in a report by Colton (Ref. 13) who also

[8] It should be noted that Reference 70, which apparently reports on one of the most complete ducted propeller programs carried out to date, does not present any actual data other than hovering performance.

measured the duct leading edge pressure distribution and presents some smoke studies of the propeller tip vortices within the duct. The work of Evans (Ref. 1) also contains some detailed velocity distributions in the static condition, as well as some detailed duct pressure distribution in non-axial flow.

In summary, the pertinent experimental data which have been published on ducted propellers have been condensed into tabular form and discussed in the foregoing paragraphs. The purpose of tabulating these reports along with some of the more basic parametric changes and measurments is twofold: first, it provides a brief outline of the test data contained in each report and thus aids in the selection of reports covering a desired parameter or type of measurement; second, by displaying the parameters varied and the measurements taken, it shows the direction which the majority of ducted propeller experiments have taken and, perhaps of more importance, indicates the areas in which little or no testing has been conducted.

4.3 Comparison of Theory and Fxperiment

Efforts to compare ducted propeller experimental work with theoretical calculations have fallen generally into several distinct categories, and each of these will be discussed in order of popularity, based upon the survey conducted.

Most common of comparisons in the literature is the comparison of observed performance with that predicted by simple momentum theory. Since the only geometric parameter entering into this theory is the diffuser area ratio, which is limited by the practical considerations of flow separation, a wide variation in design parameters not considered in the theory is possible.

As a result, the agreement varies noticeably, indicating the importance of other parameters. Perhaps the classical comparison of this type was made by Platt (Ref. 82) who tested a very limited but somewhat systematic set of shroud shapes in combination with two counter-rotating propellers of four-foot diameter under static conditions out of doors. The agreement in this case was good, with the best design tested showing about 95% of the ideal static performance indicated by simple momentum theory. On the other hand, the exhaustive experiments of Krüger (Ref. 41) showed poorer agreement with the simple theory, particularly for the shortest and longest shrouds tested. Krüger's experiments (which involved a model of about 9.5 inch diameter tested in a 4.1 foot diameter wind tunnel) further indicated that the shroud could carry significantly more than 50% of the total static thrust as predicted by simple momentum theory. (In Krüger's tests, one shroud carried 65% of the thrust.)

Comparisons of experimental results with the more sophisticated theoretical method of singularities are naturally more sparsely scattered through the literature, since a large number of variables are involved and the calculations are correspondingly more difficult, a separate lengthly calculation being required for each configuration. Very often, because of the nature of the analysis, comparisons of theory and experiment are made on the basis of a parameter which is not ordinarily measured. For example, the "internal" advance ratio may be used instead of the ordinarily measured advance ratio based on flight (or tunnel) speed. Examples of comparisons of experiment with the method of singularities can be found in References 1, 15 and 16.

A third approach is the use of experimental data to provide empirical constants to complete an analysis based on semi-empirical methods. This approach was taken by Moser and Livingston (Ref. 67) and by other investigators who have proposed modifications to momentum theory to account for various losses (e.g., Refs. 5 and 10).

Perhaps the most desirable type of comparison is that in which a theory is first developed for an optimum design which is then built and tested and the performance compared with that predicted by theory. At the present time, there is no theoretical method which yields an optimum design, so no such comparisons are available.

4.4 Auxiliary Devices

Since many of the proposed VTOL vehicles employing ducted propellers rely on the ducted propeller for both lift and propulsion, and since much of the ducted propeller work in this country has emphasized vehicle design, considerable work has been done in developing auxiliary aerodynamic devices to augment thrust and to provide the pitching and rolling moments necessary for aircraft control. Although such devices are not considered to represent an integral part of the ducted propeller problem, it is felt worthwhile to mention and document the developments along these lines. Additional information pertaining to some of these investigations can be found by referring to Tables I, II and III.

Because of the apparent conflicting duct design requirements for static operation and high forward flight speeds (in essentially axial flow), it has long been felt that some type of variable-geometry inlet might be required for ducted propellers to give good efficiency throughout the speed range. As a result, a number of auxiliary devices, including boundary layer control and circulation control, have been proposed for improving the static performance of ducted propellers. In particular, retractable flaps and slats have been tested by Krüger (Ref. 41), Johnson (Ref. 37), Regenscheit (Ref. 86) and others,[9] and a considerable amount of work has been done with distributed suction BLC (Refs. 12 and 84) and with auxiliary vanes and stators (Refs. 6, 7, 8, 9, 41, 87 and 113). More recently, experiments have been carried out in which attempts were made to expand the wake (or induce more flow through the duct) by blowing outward at the duct trailing edge (Ref. 83). In cases where the original design exhibited low static efficiencies to begin with, improvements were sometimes obtained with boundary layer control (Ref. 12). However, in no case has it been conclusively shown that any of these devices produced a higher static thrust per total horsepower input at a given disk loading than that measured by Platt for the bare ducted propeller.

Perhaps the largest portion of work along the lines of auxiliary devices has been in the direction of alleviating the large nose-up pitching moments developed on a ducted propeller which is moving through the air in a direction essentially normal to its axis. This problem is of particular concern in such vehicles as flying platforms and aerial jeeps (Refs. 1, 2, 18, 23, 59 and 89), in which some means must be provided to

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[9]Sheets (Ref. 92) did some work on slotted blades for compressors which might be applicable to ducted propellers.

supply the moments necessary for trimmed horizontal flight. Consequently, a number of investigators have tested a great variety of inlet vanes (Refs. 1, 20, 22, 23, 24, 53, 88), exit vanes (Refs. 1, 20, 22, 23, 24, 38, 52, 53, 57, 59, 88), spoilers (Refs. 11, 14, 23, 53), deformed ducts (Ref. 1) etc., in addition to the helicopter-type controls of cyclic (Ref. 59) and differential collective pitch (Ref. 1).

Such auxiliary devices generally have a deleterious effect on the overall efficiency of the ducted propeller in both hovering and forward flight. The basis for selection of a final configuration is therefore a compromise between performance and control, and the losses in efficiency associated with each auxiliary device must be determined. This requirement has, in fact, been the impetus for many of the above investigations, and the results have varied according to the particular vehicle involved.

4.5 Related Problems

In connection with ducted fan VTOL vehicle design, stability and control have represented major problems, although they are not actually a part of the basic ducted propeller problem, being more intimately tied to a particular arrangement. Several rather thorough dynamic stability analyses have been carried out (e.g., Refs. 1, 23 and 25), but it must be remembered that the significance of a dynamic analysis is tempered by the reliability of the aerodynamic stability derivative data upon which it is based. In general, reliable stability derivatives are not available, nor are methods available for predicting them theoretically. Two reasons for the lack of such data, of course, are the large number of variables involved and the large number of points required to give accurate values of the slopes of the aerodynamic data curves. Difficulties with longitudinal instabilities have been found for single-duct flying platforms in forward flight (Refs. 3, 25 and 93), and similar difficulties with lateral instabilities have been noted for multiple-duct aerial jeep vehicles (Refs. 1 and 23).

The development of multiple ducted propeller vehicles has introduced a number of problems which are not necessarily fundamental to the ducted propeller itself. From the standpoint of aerodynamics, all of these problems are embodied in the problem of aerodynamic interference or the interaction of one ducted propeller upon another. This problem is closely related to the determination of the entire flow field produced by a single ducted propeller, and a limited amount of work has been done on the interference problem itself, either by testing a ducted propeller both alone and in the presence of a second ducted propeller (Ref. 1), or by testing two ducted propellers in both the tandem and side-by-side configurations (Ref. 23).

A problem which is closely related in many ways to the ducted propeller problem is the so-called fan-in-wing concept. Here the fan is embedded in a wing surface with its axis essentially normal to the plane of the wing. The idea in using such an arrangement for VTOL aircraft is to use the fan for take-off and landing and rely on the wing for aerodynamic lift at high speeds. The problem here is somewhat different from the pure ducted propeller problem in several respects, and for this reason, such arrangements will not be considered in detail in this report. The primary difference (in the static condition) stems from the additional surface (the wing) and the associated very restricted length of duct for such "ducted" propellers.

The wing surface inhibits the flow over the shroud leading edge and produces a different flow field at the duct entrance. Since the propeller is, of necessity, located near this duct entrance, this also changes the flow through the propeller and renders it perhaps more susceptible to asymmetric dynamic loads in low-speed flight. Published material (primarily experimental) can be found in References 20, 24, 27, 32, 67, 102, 109 and 110.

The influence of ground proximity is a problem which is of major concern in all VTOL designs. In the case of the ducted propeller, the ground effect is somewhat complicated by the fact that the effect on the propeller itself is different from the effect on the duct. Several investigations have been made of the ground effect on the performance of ducted propellers in various arrangements (Refs. 14, 54, 67, 69 and 86) and measurements have been made in Reference 19 which indicates an increase of propeller thrust and a decrease in duct thrust as the ground is approached. Consequently, it might be expected that the ground effect on a ducted propeller arrangement will depend on the configuration, and the ground effect on a fan-in-wing arrangement might be quite different from that on a ducted-propeller arrangement because of the pressures induced on the wing.

It is, in fact, for the above reasons that the fan-in-wing concept itself is considered to be outside the scope of the present report, and none of the experimental reports dealing exclusively with fan-in-wing arrangements have been entered in the experimental tables. On the other hand, experimental work on both multiple-duct arrangements and ducted-propeller ground effect has been included with the isolated ducted propeller work and can be found in Tables I, II and III.

5. STATE OF THE ART - CONCLUSIONS AND RECOMMENDATIONS

A thorough search of the available literature from all parts of the globe has uncovered a total of 216 reports, papers and notes pertaining to research on ducted propellers. A study of these reports has revealed that, of the original 216, 124 contained research information pertaining to ducted propellers per se, as distinguished from compressors, propellers, rotors, and ring wings, and these are listed alphabetically in the list of references (section 6). Of these 124 references, 37 which contain pertinent experimental data have been summarized in tabular form (Tables I, II and III) to indicate the types of investigation which have been made and areas in which experimental data are lacking. A discussion of the various items appearing in Tables I, II and III is contained in section 4.2. The theoretical work does not lend itself to a similar tabular summary, owing to the many subtle but important differences of approach used by the various authors. However, the methods employed can be generally classified as falling into one of three categories: the classical method of singularities, momentum methods, and "other methods" in which attempts are made to furnish more detailed information than the momentum theory without resorting to the somewhat cumbersome method of singularities. Each of these categories has been discussed at some length, and various papers have been singled out for closer scrutiny in section 4.1.

As a result of the critical evaluation of the 124 reports selected for study, the following general conclusions and recommendations are made:

1. Owing to the nature of the flow field produced by the

propeller, the propeller shroud problem is distinct from both the plane airfoil and ring wing problems (particularly in the static condition). It can therefore hardly be expected that an airfoil shape which was developed for a completely different situation (i.e., uniform undisturbed flow) would be suitable for this application. Consequently, the development of a highly efficient shroud shape appears to require a systematic experimental program of similar magnitude to those carried out for the development of an efficient wing profile shape. Furthermore, each shroud should actually be tested in combination with a propeller designed for that shroud. Initial efforts in this direction have been made by Stipa in Italy, by Krüger in Germany, and by Soloviev and Churmack in the USSR, but these investigations were limited to axial flow and were not aimed at VTOL applications.

2. The ducted propeller problem is also distinct from the compressor problem. A good compressor is therefore not necessarily a good ducted propeller. That is, a device which produces the largest pressure increase for the smallest expenditure of kinetic energy does not necessarily produce the most static thrust per horsepower at a given disk loading. The essential difference arises from the importance of the distribution of thrust between shroud and propeller. It can be shown mathematically that an efficient ducted propeller must carry as large a portion of the total thrust on the shroud as possible. This is the primary reason that the most efficient ducted propellers thus far developed for static

operation have not been those employing the so-called bell-mouth shroud shape as was expected earlier.

3. In spite of the very elegant techniques which are available for dealing with the ducted propeller problem as a distribution of elementary vortex rings (method of singularities), either the shroud vorticity distribution or the shroud shape must be assumed. Therefore, neither the optimum vorticity distribution nor the required shroud shape and propeller design are known at this time. Even the ideal performance to be expected of such an optimum design is unknown.

4. The relationship of the final wake characteristics to conditions at the shroud exit is unknown and is ordinarily assumed in applications of the momentum theorem in an effort to obtain explicit results. It is this relationship that would seem to require investigation and may provide the missing link for determining an optimum design by the method of singularities. That is, if one could determine an optimum velocity distribution at the duct exit which would assure optimum performance by generating a uniform final wake of maximum cross-sectional area, then one could design an optimum shroud shape by the method of singularities and an optimum propeller for that shroud by existing propeller design techniques.

5. The static performance predicted by "simple momentum theory" (i.e., assuming a wake of constant diameter) has essentially been

achieved by Platt (Ref. 82) without either high-solidity fans or bell-mouth duct. However, whether or not this theory represents the best possible static performance, and, if not, how to improve on it, remain open questions. For the high speed regime (i.e., axial flow), Grose (Ref. 26) has measured propulsive efficiencies of 0.69 at a free-stream Mach number of 0.6.

6. The importance of scale effect on ducted propeller characterization has apparently received little attention. Experimental data on geometrically similar models of different scale (in sufficiently large wind tunnels) are needed for the proper evaluation of scale effect.

7. A number of investigators have studied special ducted propeller problems such as the effects of diffuser angle, propeller solidity, propeller position, tip clearance, blade twist, etc. In most instances, however, these effects were studied under very special circumstances (e.g., fixed-pitch propellers, specified shroud, etc.) so that it is difficult to draw any general conclusions. It does appear that there is agreement on one of these effects: specifically, that excessive tip clearance has a deleterious effect on performance. The effect of blade twist is a subject of controversy, since conflicting results have been obtained by different investigators (e.g., Refs. 18, 41 and 13, 58).

8. Simple comparison plots of ducted propeller static performance in which full-scale flying test beds and wind-tunnel models are

directly compared can be quite misleading, owing to differences in transmission losses, possible scale effects, and different methods of applying corrections to measured values of thrust and power. Therefore, no such comparisons have been presented here.

9. There appears to be little agreement regarding the type of corrections (if any) to be applied to wind-tunnel data for ducted propellers. No attempt has been made to develop tunnel wall corrections for ducted propellers in non-axial flow, although static tests of the same model inside and outside the wind tunnel have indicated differences in thrust of the order of 15% even at relatively low disk loadings (e.g., Ref. 67).

In view of the interdependence of the effects of the various parameters, it is considered essential that the effect of each variable be investigated under variable constraints. Thus, if, for example, it is proposed to investigate the effect of tip clearance on the static performance of ducted propellers, one should also

a) vary propeller pitch setting to determine optimum setting for each case,

b) test effect with several systematically related shroud shapes designed to avoid separation,

c) vary propeller position within the shroud,

d) vary propeller twist and planform,

e) measure total thrust, shroud thrust, power supplied, shroud pressure distribution, and velocity distribution ahead and behind the propeller.

Compromises will, of course, have to be made for practical reasons, but the ducted propeller problem cannot be satisfactorily handled by testing isolated effects with all other variables fixed. The results of such testing can be seen throughout the literature. Addition of any new parameters (e.g., boundary layer control) further intensifies the need for a more general investigation.

It should be pointed out that for many of the questions (both experimental and theoretical) discussed above regarding the aerodynamics of ducted propellers, even a static investigation would be useful, thereby reducing the number of parameters by two (advance ratio and tilt angle). Performing the tests either outdoors or in a sufficiently large room has the additional advantage of eliminating tunnel wall effects.

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TABLE I

SUMMARY OF EXPERIMENTAL DUCTED PROPELLER WORK
STATIC CONDITION

Ref. No.	Vary Duct Shape	Vary Pitch	Attain Opt. Pitch	Vary No. of Blades	Vary Blade Design	Measure Total Thrust	Measure Power	Measure Prop. Thrust	Measure Duct Thrust	Duct Pressure Distr.	Velocity Survey	Remarks
1	X	X	X			X	X			X	X	In and out of tunnel. Single and tandem ducts. Prop. location varied.
11	X					X				X		Full scale truck tests. Power estimated from RPM.
12					X*	X	X			X	X	Tests in large room. *Blade twist. Smoke studies.
13	X	X	X	X	X	X	X		X		X	In and out of tunnel. Blade twist and planform.
22	X	X			X	X	X			X	X	Tandem ducts. Full scale and W. T. model. Inlet and exit vanes.
24		X		X	X	X	X				X	Single duct and fan-in-wing. Inlet and exit vanes.
26	X	X	X				X	X	X			
28	X					X	X		X			
33						X	X					Full scale and model boat.
34	X					X	X	X	X	X		Not truly static. Water tests. Prop. location varied.
35	X			X			X		X	X		Full scale (4 ft.), outdoors. Sound measurement. Tip clearance varied.
37	X											Approximate power. Leading edge slats.
41	X	X	X*		X	X	X	X	X	X	X	Not truly static. Blade twist, centerbodies, stators. *Not always. Ducts with and without props.
46	X			X		X	X	X				Lip radius, diffuser angle.
57						X						Free-flight model tests with vanes.
58				X	X	X	X			X	X	Model and full scale. Blade planform and twist.
59		X				X	X					Full scale truck tests. Tandem ducts, exit vanes, tufts.
67	X	X	X		X	X	X	X		X	X	In and out of tunnel. Fan-in-wing and ducted fan. Ground effects, blade twist.
70	X	X	X	X	X	X	X			X*	X*	*Data not presented. *Model details omitted.
74	X					X	X					Varied lip radius.
82	X	X	X				X	X	X	X	X	Full scale (4 ft.).
86	X	X		X		X	X					Ground effect. Inlet and outlet rings.
87				X		X	X					Single and dual rotation props. Stators.
94	X	X		X	X	X	X		X	X		9 ducts with and without props. Water tests. Blade width.
97	X				X	X	X	X	X			Prop. at duct leading edge. Long ducts.
113	X	X	X**	X		X	X		X	X**		*Composite of 3 reports. **Not always. Inlet and exit vanes, inlet flaps.

TABLE II

SUMMARY OF EXPERIMENTAL DUCTED PROPELLER WORK
AXIAL FLOW

Ref. No.	Vary Duct Shape	Vary Pitch	Attain Opt. Pitch	Vary No. of Blades	Vary Blade Design	Measure Total Thrust	Measure Power	Measure Prop. Thrust	Measure Duct Thrust	Duct Pressure Distr.	Velocity Survey	Remarks
4		X	X		X	X	X	X	X	X	X	Very low disk loading - 0 to 3 psf.
26		X	X				X	X	X			Tunnel Mach No. up to 0.6.
28	X					X	X		X			With and without shroud.
33						X	X					Full scale and model boat.
34	X					X	X	X	X	X		Water tests. Prop. location varied.
41	X	X	X*		X	X	X	X	X	X	X	*Not always. Blade twist, centerbodies. Ducts with and without props.
46	X			X		X	X	X				Lip radius, diffuser angle.
58					X	X	X			X	X	Full scale. Blade twist, tufts.
94	X	X		X	X	X	X		X	X		9 ducts with and without props. Water tests.
97	X				X	X	X	X	X			Prop. at duct leading edge. Long ducts.
105	X	X	X			X	X		X		X	Open water tests.
106	X	X	X	X	X	X	X		X		X	Open water tests.
113	X	X	X*	X		X	X		X	X*		*Not always. Inlet and exit vanes, inlet flaps.

TABLE III

SUMMARY OF EXPERIMENTAL DUCTED PROPELLER WORK
NON-AXIAL FLOW

Ref. No.	Vary Duct Shape	Vary Pitch	Vary No. of Blades	Vary Blade Design	Measure Total Forces	Measure Total Moment	Measure Power	Measure Prop. Forces	Measure Duct Forces	Measure Prop. Moment	Measure Duct Moment	Duct Pressure Distr.	Velocity Survey	Remarks
1	X	X			X	X	X					X		Single and tandem ducts. Varied prop. location.
11	X				X	X						X		Full scale truck tests. Power estimated from RPM.
15	X	X	X	X	X	X	X		X		X		X	Blade twist and planform.
23	X	X			X	X	X						X	Tandem ducts. Full scale and W. T. model. Inlet and exit vanes.
24					X	X	X						X	Single duct and fan-in-wing. Inlet and exit vanes.
26		X					X	X*	X					*No prop. normal force. Tunnel Mach No. up to 0.6. Nearly axial flow, $\alpha \leq 6^{\circ}$.
37					X*									Free-flight model tests with vanes. *Thrust only.
59					X	X	X							Full scale truck tests. Tandem ducts, exit vanes, tufts.
67		X			X	X	X	X				X	X	Fan-in-wing and ducted fan. Ground effects.
74					X	X								
113	X	X	X		X	X	X		X*					*No duct normal force. Inlet and exit vanes, inlet flaps.

APPENDIX A

LIST OF AGENCIES, INSTITUTIONS AND COMPANIES CONTACTED FOR SURVEY

1. U. S. Government Organizations

   Armed Services Technical Information Agency, Arlington, Virginia

   Bureau of Aeronautics, Washington, D. C.

   Bureau of Ships, Washington, D. C.

   David Taylor Model Basin, Washington, D. C.

   National Aeronautics and Space Administration, Langley Air Force Base, Virginia

   Office of Naval Research, Washington, D. C.

   Transportation Research and Engineering Command, Fort Eustis, Virginia

   Wright Air Development Center, Wright-Patterson Air Force Base, Ohio

2. U. S. Universities

   Georgia Institute of Technology, Atlanta, Georgia

   The Johns Hopkins University, Silver Spring, Maryland

   Massachusetts Institute of Technology, Cambridge, Massachusetts

   Mississippi State College, Starkville, Mississippi

   Polytechnic Institute of Brooklyn, Brooklyn, New York

   Princeton University, The James Forrestal Research Center, Princeton, New Jersey

   Stanford University, Stanford, California

   University of Wichita, Department of Engineering Research, Wichita, Kansas

3. U. S. Companies

   Aerophysics Development Corporation, Santa Barbara, California

Bell Aircraft Corporation, Aircraft Division, Buffalo, New York

Bell Helicopter Corporation, Ft. Worth, Texas

Chrysler Corporation, Defense Engineering Division, Detroit, Michigan

Collins Aeronautical Research Laboratory, Cedar Rapids, Iowa

Cornell Aeronautical Laboratory, Inc., Buffalo, New York

Curtiss Wright Corporation, Propeller Division, Caldwell, New Jersey

Doak Aircraft Company, Inc., Torrance, California

Eastern Research Group, New York, New York

Fairchild Engine and Airplane Corporation, Fairchild Aircraft Division, Hagerstown, Maryland

Fletch-Aire, Inc., Newton, New Jersey

General Electric Company, Flight Propulsion Laboratory, Cincinnati, Ohio

General Motors Corporation, Allison Division, Dayton, Ohio

Goodyear Aircraft Corporation, Akron, Ohio

Grumman Aircraft Engineering Corporation, Bethpage, New York

Kaman Aircraft Corporation, Bloomfield, Connecticut

Longren Aircraft Company, Torrance, California

Piasecki Aircraft Corporation, Philadelphia, Pennsylvania

Ryan Aeronautical Company, San Diego, California

United Aircraft Corporation, Hamilton Standard Division, Windsor Locks, Connecticut

United Aircraft Corpor ion, Research Department, East Hartford, Connecticut

Vertol Aircraft Corporation, Morton, Pennsylvania

4. Foreign Organizations

Australia: Australian Council for Aeronautics, Melbourne, Australia

Belgium:	Centre National d'Etudes et de Recherches Aéronautiques, Bruxelles, Belgium
Canada:	Defence Research Board, Department of National Defence, Ottawa, Canada
	University of Toronto, Toronto, Canada
Denmark:	Military Research Board, Defence Staff, Kastellet, Copenhagen Ø, Denmark
France:	Office National d'Etudes et de Recherches Aéronautiques, Chatillon-sous-Bagneux (Seine), France
Germany:	Deutche Forschungsanstalt für Luftfahrt e.V (DFL), Institut für Flugmechanik, Braunschweig, Flughafen, Germany
	Lehrstuhl und Institut für Angewandte Mathematik, Technische Hochschule Karlsruhe, Karlsruhe, Germany
	Lehrstuhl für Flugzeugbau an der Technischen Hochschule Stuttgart, Stuttgart, Germany
	Zentralstelle der Luftfahrtdokumentation (ZLD), München, Flughafen, Germany
	Zentrale für wissenschaftliches Berichtswesen der DVL, Mülheim/Ruhr, Germany
Great Britain:	British Joint Services Mission, Washington, D. C.
	Ministry of Supply, London, W.C.1, England
	Rolls Royce, Ltd., Derby, England
	Royal Aeronautical Society, London, W. 1, England
	Royal Aircraft Establishment, Farnborough, Hants, England
Greece:	Greek National Defence General Staff, B. MEO, Athens, Greece
Iceland:	Director of Aviation, C/o Flugrad, Reykjavik, Iceland
Italy:	Centrol Consultivo Studi e Ricerche, Ministero Difesa, Rome, Italy
Japan:	Physical Society of Japan, University of Tokyo, Tokyo, Japan

Luxemburg:	Luxemburg Delagation to NATO, Paris, France
Netherlands:	Netherlands Delegation to AGARD, Delft, Holland, Netherlands
	The Netherlands Ship Model Basin, Wageningen, Netherlands
Norway:	Royal Norwegian Air Force, Oslo, Norway
Portugal:	Subsecretariado da Estado da Aeronautica, Lisbon, Portugal
Turkey:	Erkaniharbiyei Umumiye Riyaseti, Ilmi Istisare Kurulu Mudurlugu, Ankara, Turkey
Union of South Africa:	South African Council for Scientific and Industrial Research, Pretoria, Union of South Africa

APPENDIX B

DUCTED FAN SYMPOSIUM

A symposium was held at the Massachusetts Institute of Technology on December 4, 5 and 6, 1958, for the purpose of promoting an exchange of information among the various workers in the field of ducted propellers. The symposium was sponsored jointly by the United States Army Transportation Corps and the Massachusetts Institute of Technology, and was attended by representatives of the following organizations:

Bell Aircraft Corporation, Buffalo, New York

Bell Helicopter Corporation, Fort Worth, Texas

Bureau of Aeronautics, Washington, D. C.

Chrysler Defence Engineering, Detroit, Michigan

Collins Radio Company, Cedar Rapids, Iowa

Cornell Aeronautical Laboratory, Buffalo, New York

David Taylor Model Basin, Washington, D. C.

Doak Aircraft Company, Torrance, California

General Electric Company, Cincinnati, Ohio

Georgia Institute of Technology, Department of Aeronautical Engineering, Atlanta, Georgia

Goodyear Aircraft Corporation, Akron, Ohio

Grumman Aircraft Engineering Corporation, Bethpage L.I., New York

Hamilton Standard Division, United Aircraft Corporation, Windsor Locks, Connecticut

Hiller Aircraft Corporation, Palo Alto, California

Langley Research Center, NASA, Langley Air Force Base, Virginia

Massachusetts Institute of Technology, Cambridge, Massachusetts

Mississippi State College, Starkville, Mississippi

National Research Council, Ottawa, Canada

Office of Chief of Research and Development, U. S. Army, Washington, D. C.

Office of Chief of Transportation, U. S. Army, Washington, D. C.

Office of Naval Research, Washington, D. C.

Princeton University, Princeton, New Jersey

Piasecki Aircraft Corporation, Philadelphia, Pennsylvania

Research Department, United Aircraft Corporation, East Hartford, Connecticut

Transportation Research and Engineering Command, Fort Eustis, Virginia

University of Wichita, Wichita, Kansas

Vertol Aircraft Corporation, Morton, Pennsylvania

Wright Air Development Center, Wright-Patterson Air Force Base, Dayton, Ohio

As a result of the above symposium, the papers listed below were made available to the participants:

Campbell, J. P.: Ducted Fan Research at the NASA-Langley Research Center. (Copies unavailable)

Collier, W. R.: Notes on a Convertible VTOL Propulsion System. General Electric Company, Flight Propulsion Laboratory Department. (Available copies limited to 25)

Anon.: Preliminary Test Results of a Twin-Shrouded Propeller Arrangement. Collins Radio Company. (Copies available)

Anon.: STOL/VTOL Research at Cornell Aeronautical Laboratory, Inc. (Copies available through Cornell Aero Lab Library)

Anon.: Shrouded Propeller Investigation at the David Taylor Model Basin. (Copies available)

Gorton, J. V.: Chrysler Defense Engineering's Work in the Ducted Fan Field. (Available copies limited to 30)

Grahame, W. E.: A Review of Ducted Fan Research at Grumman Aircraft Engineering Corporation. (Copies unavailable - same material in IAS Report 59-59, see Reference 20)

Grose, R. M.: Report to the Ducted Fan Symposium on an Investigation of Shrouded Propellers Conducted by the Research Department of United Aircraft Corporation, Report UAR-C404. (Paper included in Reference 26)

Anon.: Summary of Hamilton Standard Activity on Shrouded Propellers for Period 1957 - 1958. United Aircraft Corporation (Digest of: Rohrbach, C.: Analytical Study to Determine the Important Parameters of Vertical Lift Shrouded Propellers, Hamilton Standard, Division of United Aircraft Corporation. WADC Technical Report 58-262, May, 1958. (ASTIA AD 155 589))

Jackes, A. M.: Ducted Propeller Developments at Bell Aircraft. (Copies available)

Johnson, R. S. Jr.: The Ducted Fan as Applied to the Convoplane Concept. Goodyear Aircraft Corporation. (Copies available)

Anon.: Ducted Fan Research at Massachusetts Institute of Technology. (Copies available)

Nelson, N. E.: The Ducted Fan in VTOL Aircraft Design. Doak Aircraft Company, Inc. (Copies available)

Anon.: Ducted Fan Research at Princeton University. (Copies available)

Raspet, A.: Ducted Propeller Studies at Mississippi State University, Research Note No. 7. (Available on loan)

Sissingh, G. J., Sacks, A. H.: Comments on Present Ducted Fan Research at the Advanced Research Division of Hiller Aircraft Corporation. (Copies available)

Stepniewski, W. Z.: Vertol's Work in Ducted Fans - Resume of a Presentation Given at MIT Ducted Fan Symposium. (Copies available)

Wattson, R. K.: Some Results of Wind-Tunnel Tests of Shrouded Propellers. University of Wichita. (Copies unavailable)

APPENDIX C

LIST OF SYMBOLS

A_e Duct exit area

A_f Final wake cross-sectional area (at infinity downstream)

A_p Propeller disk area

C_{T_p} Propeller thrust coefficient, $\dfrac{T_p}{\frac{1}{2}\rho V_o^2 A_p}$

M Static figure of merit, $\dfrac{T}{P}\sqrt{\dfrac{T/A_p}{2\rho}}$

P Power input to propeller

Δp Pressure jump across propeller disk

T Total thrust (axial)

T_p Propeller thrust (axial)

v Axial velocity at propeller disk

v_f Final wake velocity (axial flow)

V_o Free-stream or flight velocity

η Propulsive efficiency (axial flow), $\dfrac{T V_o}{P}$

η_s Static efficiency, $\dfrac{\text{slipstream kinetic energy}}{\text{power input}}$

ρ Fluid mass density

Subscript

i Ideal

BIBLIOGRAPHICAL CONTROL SHEET

1. Originating Agency and/or Monitoring Agency:

   O. A.: Hiller Aircraft Corporation, Palo Alto, California
   M. A.: Office of Naval Research, Air Branch, Washington 25, D. C.

2. Originating Agency and/or Monitoring Agency Report Number:

   O. A.: Report No. ARD-232

3. Title and Classification of Title: Unclassified

   Ducted Propellers - A Critical Review of the State of the Art

4. Personal Authors: A. H. Sacks and J. A. Burnell

5. Date of Report: 26 June 1959

6. Pages: 71

7. Illustrative Material: Three (3) Tables

8. Prepared for Contract No.: Nonr 2677(00)

9. Prepared for Project No.: NR 212-074/7-14-58 (Air Branch)

10. Security Classification: Unclassified

11. Distribution List: See attached list, supplied by Ref: ONR Ltr. of 20 July 1959, ONR: 461: GEM: fcw.

12. Abstract:

A critical survey of the state of the art of ducted propellers, discussing both theoretical and experimental research along with some recommendations for future research.

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